

Chapter 25 Galaxies and Dark Matter

Dark Matter in the Universe

We determined that we must have a significant amount of dark matter in our galaxy to account for the large gravitational attraction that holds on to our outer stars. The big question is do other galaxies contain dark matter? Can we measure the masses of other galaxies? The answer is yes. Despite their large sizes, they follow the same rules that our solar system follows. We will use Newton's law of gravity.

Galaxy Masses

We can determine the masses of some spiral galaxies by looking at their rotational curves. This looks at the speed of the stars as you move farther from the nucleus. Figure 25.1 shows us the rotational curves for several galaxies compared to the Milky Way. Distant galaxies are too far away to draw detailed curves. We can look at the line broadening in the spectrum of the galaxy. Line broadening can occur due to rotation of the object, so the broader the line, the faster it is rotating. That means that when we estimate the size of the galaxy, we also estimate the mass of the galaxy. Similar techniques have been applied to ellipticals and irregulars. To determine mass farther out we look at binary galaxy systems. Figure 25.2a The galaxies may be hundreds of kpc away from each other and the rotation may take billions of years. By looking at them and estimating their period and semi-major axis we can estimate the masses. But masses determined this way are uncertain. But we can get better accuracy by doing this for many galaxies. This allows us to gather reliable statistical information. Figure 25.2b shows us a galaxy cluster. We can measure the speed of a galaxy moving within the cluster and determine the mass of the cluster needed to hold the galaxy in the cluster. We are assuming that the galaxy is gravitationally bound in the cluster. By doing this type of work, we have found the range of masses for spirals, ellipticals, irregulars, and clusters of galaxies.

Visible Matter and Dark Halos

Looking at the rotational curves shows that the curves remain flat or even rises a little. This says that even after the visible galaxy ends, they must some kind of invisible halo to account for the mass. This appears to be 3 to 10 times the mass of the galaxy itself. Some of the least visible galaxies have the greatest amount of dark matter in them. They call them *dark galaxies*. That would make them very hard to see so we must look for other evidence. Figure 25.3 shows a galaxy that may have encountered a dark galaxy. That would account for the long streamer of gas coming off the galaxy and no visible galaxy that would have caused it. When we look at galaxy clusters we find that the mass of the dark matter is 10 to 100 times the visible mass. This shows that the idea of dark matter is not limited to our galaxy, but rather is throughout the universe. This leads astronomers to believe that the universe is made up of about 90 % dark matter.

Intracluster Gas

Astronomers have also found in the clusters large amounts of intracluster gas. This gas is extremely hot, millions of K. This means that they radiate huge amounts of energy in the X-ray region of the spectra. The X-rays are centered on and comparable in size to the

cluster. Figure 25.4 The intracluster gas can be seen in some radio galaxy lobes. IN some systems known as *head-tail radio galaxies* the lobes seem to form a tail out behind the galaxy. Figure 25.5 This is because the galaxy is moving through its parent cluster (the Perseus Cluster) and the material is being swept behind it. There is so much gas in these clusters that it can't have been produced by the galaxies themselves. It must be primordial in nature. It never became part of any galaxy. Some of the gas has been ejected by galaxies because there is some carbon, nitrogen, and so on in the gas. Why is the gas so hot? Just like the galaxies in the cluster, the gas is moving at similar speeds (maybe 1000 km/sec) and since temperature is a measure of particle speeds, the gas is hot. All of this hot gas means that there must be a substantial amount of dark matter to keep this hot gas from leaving the cluster. Without a huge gravitational attraction the gas would escape from the cluster.

Galaxy Collisions

You would think that within congested clusters such as the Virgo Cluster that you would have collisions between galaxies. Well you would be right. There are many examples of colliding galaxies. Figure 25.7 shows the aftermath of such a collision. It is thought that one of the 2 small ones to the right is the culprit. Figure 25.8 shows a close encounter between 2 galaxies that hasn't yet led to a collision. Apparently the small galaxy doesn't have enough energy to pull away from the large galaxy. There is no way that we can see a collision from the beginning to the end. Figure 25.9 shows the outcome of 2 galaxies that interacted with each other. They are called the Antennae for an obvious reason. Most galaxies have such a slow speed through space that when a collision occurs you have the 2 galaxies merge into one galaxy. This is called *galactic cannibalism*. Even though it completely rearranges the galaxy's structure, it doesn't affect the stars in the galaxies.

Galaxy Formation and Evolution

We are currently in the process of understanding how galaxies may form and evolve over time. We really understand star formation, but we don't know what occurred back at the time of galaxy formation. One other thing that can make understanding galaxy formation hard is that galaxies may have undergone several collisions since their birth.

Mergers and Acquisitions

In the early universe there would have been many pre-galactic blobs of gas. Most astronomers believe that numerous mergers occurred to produce larger structures. Large red shift galaxies are much smaller than close by galaxies so this seems to help support this idea. Figure 25.10b and 25.11 shows some of these objects that are up to 5 billion parsecs away. The small bluish patches are faint galaxies that have only a few percent the mass of the Milky Way. Figure 25.10c shows a close up of some of these blobs. Each one seems to contain about several billion stars. We see them as they were 10 billion years ago.

Interactions and Evolution

Most galaxies if they are left alone will evolve as we would expect; the nucleus forms first and ages as the disk forms and starts to form stars. But most galaxies aren't alone.

Gravitational interaction may rearrange the structure of both galaxies and leads to star birth. It occurs so intensely that they call these galaxies *starburst galaxies*. Figure 25.12 These interactions may also dump fuel on a central black hole causing all kinds of activity. Computer simulations show that halos play a very important part in galaxy interactions. Figure 25.13 shows an example of galactic cannibalism. Figure 25.14 shows a computer simulation between 2 galaxies in which one galaxy causes the other galaxy to form spiral arms where there weren't any before. This would have taken several hundred million years to happen.

Making the Hubble Sequence

We now realize that galaxies do not evolve and follow the Hubble Tuning fork model. But we are also seeing how galaxy mergers might cause the evolution to occur this way. A major merger can destroy a galaxy's disk, causing tremendous star birth and causing huge amounts of gas to be ejected into the intergalactic space where it is heated up to extremely high temperatures. What you now have is what looks like an elliptical galaxy. Minor mergers usually leave the larger galaxy intact with the same classification that it had before. Some of this evidence comes from huge clusters of galaxies. Down in the core of these clusters you only find elliptical galaxies. That would support our idea that the disks of spirals are very fragile and would not survive a collision. We are learning, but nothing is clear cut so our job is much harder.

Black Holes and Active Galaxies

Let's see how quasars and active galaxies fit into the evolution of the galaxies. One of the things that we note is that quasars are found in much higher numbers the farther away you look says that they were more prevalent in the past. Most astronomers agree that quasars are an early stage of the development of the galaxies.

The Quasar Epoch

Astronomers believe that active galaxies are powered by material falling onto a black hole. But the question of where these supermassive black holes came from keeps popping up. Since the brightest known quasars devour about $1000 M_{\text{sun}}$ every year a million years would require about 1 billion M_{sun} for this to occur. That means that the quasar phase is short lived, maybe only a few million years. To make a quasar we need a black hole and lots of material to feed it. In the early universe dust and gas would have been plentiful, but the black holes weren't. What you probably had were a number of smaller black holes that fell to the center as it formed up. As they did they merged together to form a single black hole. As galaxies merged, so did their black holes. This would eventually account for the supermassive black holes at the cores of most galaxies. No one had ever seen that until 2002 when the Chandra satellite found a binary pair of black holes. Figure 25.15 The 2 parent galaxies merged about 30 million years ago and it is predicted that the black holes will merge in about 400 million years. They are currently about 1000 pc apart. The distant galaxies that house the quasars are very dim when compared to their quasars. With the Hubble Space Telescope we can now see some of the host galaxies. Figure 25.16

Active and Normal Galaxies

As time went on, mergers probably replenished the quasars fuel supply for the black hole. When this happened, there was less and less fuel and the quasars finally turned off. That was about 10 billion years ago and would have ended the quasar epoch. That is why the only quasars that we see lie billions of light years away from us. The black holes didn't disappear though. We see these black holes as active galaxies. But that goes back to fuel supply. That leads us to the assumption that all galaxies have a black hole in the core. We now have evidence that the Milky Way has a supermassive black hole in its core. This black hole has a mass around 3 million M_{sun} . It is not currently active, but if we supplied fuel to it the black hole would wake up. We have imaged a galaxy called NGC 4258 which lies about 6 Mpc away from us. The resolution was hundreds of times better than the Hubble Space Telescope and they found a swirling cloud moving around the galaxy's center. Figure 25.17 The speed of the cloud indicates a mass of about 40 million M_{sun} packed into a region of space less than .2 pc across. If it is true that most big galaxies have supermassive black holes at their centers, they must have been brilliant quasars in the past.

Active Galaxy Evolution

The galaxy merger scenario may provide clues as to the connection between active and normal galaxies. Figure 25.18 The largest black holes are found in the largest galaxies, suggesting that when mergers occurred, the black holes also merged. This leads us to the giant elliptical galaxies. That also explains why the brightest active galaxies are giant ellipticals. As evidence came in, many theories went by the wayside until the only one left was the black hole theory. At one time it was considered very extreme, but as it happens it is now widely accepted.

The Universe on a Large Scale

Many galaxies are found in clusters. Figure 25.20 shows several large clusters found near the Local Group. Every point is a single galaxy.

Clusters of Clusters

As we continue to scan the skies, we are now finding that the clusters are found in clusters themselves called superclusters. Figure 25.20 shows us the local supercluster called the Virgo Supercluster. This is about 20 – 30 Mpc out from the Virgo cluster. Figure 25.21 shows a 3 dimensional picture of the cluster. The Local Supercluster is about 40 – 50 Mpc across and contains about $10^{15} M_{\text{sun}}$ and it is very irregular in shape.

Redshift Surveys

As we look farther out, the question is whether there is any structure to the galaxies and clusters. The answer is yes. Figure 25.22 shows part of a survey of galaxies. This slice shows galaxies out to about 200 Mpc from us. Since we are using redshifts to determine the distances, it is called the *redshift survey*. As you look, you begin to see that the structure is definitely nonrandom. You can see a large numbers of galaxies that are arranged in a straight line called the *Great Wall*. The blank spots between the galaxies are called *voids*. The biggest of the voids is 100 Mpc across. As we expand the search,

Figure 25.23, you see many features such as filaments, voids and walls, but nothing bigger. Figure 25.23 shows us about 24,000 galaxies.

Quasar Absorption Lines

How do we study the structure of the universe? Much is dark as we have seen and the luminous part is very dim. To help we will look at quasar images and spectra to determine a partial picture of the intervening space. The problem with that is that we can only look where quasars are found. We have found that many quasars are showing absorption features that are redshifted much less than the quasar itself. They believe that it is intervening dust that is much closer to us than the quasar. It is probably part of an invisible galaxy that is in our line of sight with the quasar. Figure 25.24 shows a forest of absorption lines. This tells astronomers about the space between us and the quasar.

Quasar “Mirages”

In 1979 astronomers found a binary quasar. Both quasars had the exact same spectra and the exact same redshift. Hmmm Closer study of the quasars proved that it was actually only one quasar. Figure 25.25 What could cause that to happen? The answer is gravitational lensing. A very massive body is between us and the more distant quasar and the light is bent around the basically invisible object. Figure 25.26 In Figure 25.27 you can see what is called the Einstein Cross. Here you have 4 images of the same object. We currently know about 2 dozen of these lenses.

Mapping Dark Matter

We are currently using lensing events to help map out dark matter. As you can see in Figure 25.28 you can see how the images of faint, distant clusters are being bent. The amount of bending allows us to calculate how much mass must be present to cause the distant object to bend like that. By carefully measuring the distortions of space we can map out the distribution of mass on much larger scales. Figure 25.29 shows us a map of dark matter many parsecs out from the center of the cluster.